NASA TECHNICAL MEMORANDUM

NASA TM X-58053
November 1970

GUIDANCE AND CONTROL CONSIDERATIONS FOR ADVANCED MANNED SPACE MISSIONS

Presented at the Institute of Navigation
National Space Meeting
Houston, Texas, April 1969

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

GUIDANCE AND CONTROL CONSIDERATIONS FOR ADVANCED MANNED SPACE MISSIONS

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ABSTRACT

The directions that future manned navigation, guidance and control developments are likely to take are explored. The scope of these future developments is shown to be encompassed by the types of space transportation systems to be used and the objectives of the exploration bases to be developed. The requirements for an earth orbital exploration base and its supporting logistics shuttle are considered in the context of our past experience and the unique requirements of the future. It is shown that we will be transitioning from programs that are principally developmental in nature, to programs which are more operationally conditioned. This fact, coupled with the resulting longer duration missions, indicates a need for a reconsideration of our manned navigation, guidance and control system approaches. The mechanization challenge for the future will not be in meeting discrete performance requirements. It will result from the need to meet stringent reliability goals that will, more than ever before, be intimately associated with program costs.

INTRODUCTION

As the Apollo Program approaches its culmination and the characteristics of NASA's advanced manned mission become more definitive, it is timely to consider the directions to be taken in the development of guidance and control systems for these future programs. The directions that these developments take will be determined by three factors. The first is the logical top-to-bottom consideration whereby the mission, system, and subsystem requirements are defined more or less sequentially. The second is the technological state of the art at the time these developments are undertaken, for it defines what is possible. The third factor might be considered a filter through which the first two must pass to get the needed results. It represents the application of our background and experience in previous manned guidance and control developments to these new programs. In essence, our future requirements will be met with a logical and evolutionary approach founded on the integral sum of knowledge from our previous manned programs. That is not to say that we will necessarily use the same techniques or the same hardware as we largely have, for example, in our Applications

Program. That program is designed to amortize our rather substantial Apollo hardware investment with an expanded programmatic scope. The techniques may change and the hardware will undoubtedly be different but our new developments will, without question, be conditioned by what we have learned in the Mercury, Gemini, and Apollo Programs.

The purpose of this paper is thus to explore, with some generalities and some specifics, the first and third of these three factors in an attempt to define what the probable directions for our future manned guidance and control developments will be. The second factor, the technological state of the art, will only be touched on as necessary to amplify the other considerations. After briefly discussing the likely future manned missions, consideration is given to some of their specific and implied navigation, guidance and control requirements. Then, using the results of our other manned programs, particularly Apollo, the implementation of some of these new requirements is discussed in the light of our past solutions.

FUTURE MANNED MISSIONS

As of this date the actual manned space flight program to be undertaken in the future has not been identified in detail. Exact launch dates, specific flight objectives, rates at which launches are to occur, etc., are not defined. However, the potential elements of the manned space flight program and their anticipated phasing are known and are shown in figure 1. Note that this figure merely shows flight blocks approximately oriented in time. The Apollo Program's objective of landing a man on the

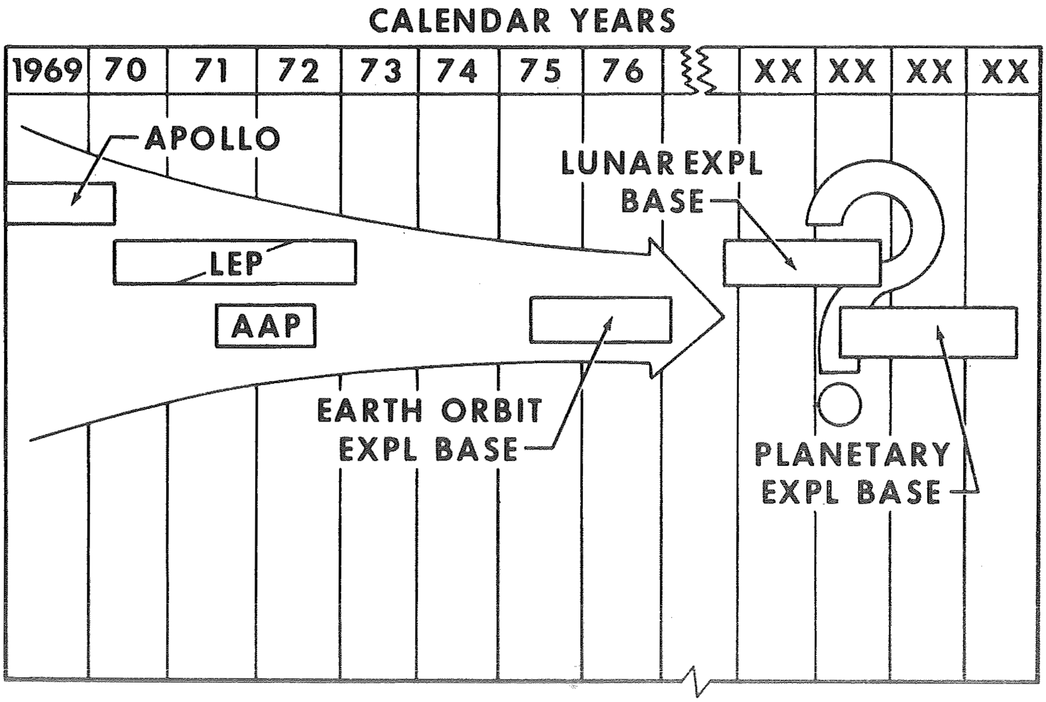

Figure 1. Manned Space Flight Program

moon and returning him should be completed in the calendar year 1969 to 1970 time period. Next will follow the Lunar Exploration Program (LEP), which in its early phase will consist of several flights to the various primary Apollo landing sites. These flights will strive for the utmost that the Apollo Spacecraft, with little or no change, can provide in the achievement of the Apollo Lunar Surface Experiment Package (ALSEP) scientific objectives and in lunar exploration potential. As currently planned, the five-flight Apollo Applications Program (AAP) will fly in the calendar year 1971 to 1972 time period. Whether AAP will fly concurrently with the LEP, as shown, has not been determined. The latter portion of the LEP will be flown in the 1971 to 1972 calendar year time period. It should be noted that the balance between the number of flights in this phase and in the first one is yet to be determined. Operations in the later phase are to be conducted with improvements to the Apollo hardware which will allow landings at more challenging lunar locations with more landed payload and extended stay times. These missions could involve dual landings with the additional landing being accomplished by either a manned or an unmanned vehicle; and potentially, they are to include the operational use of lunar flying units and lunar rover vehicles.

The next three blocks of flights represent the operational periods of earth orbit, lunar, and planetary exploration bases. Only the earth orbital exploration base is oriented in time, for it is beginning to evolve as a definitive concept which could begin flight operations in the 1975 to 1976 time period. This earth orbital base, which could weigh of the order of a million pounds, is being conceived as a true orbital facility. Initial segments of the base used in early operations will have a minimum lifetime of 2 years, but the base itself will have as a goal a 10-year life. It includes periodic personnel changes and resupply flights with a shuttle vehicle on a 90- to 180-day cycle. It should be pointed out here that the goal of a very long exploration base lifetime and a sustained rate of logistic shuttle flights will make it extremely important to minimize this program's operational costs.[1] In the Mercury, Gemini, and Apollo Programs, which were principally developmental, the nonrecurring and recurring costs were of the same order of magnitude.[2] This earth exploration base and its objectives will be the principal focus on which this paper centers. The lunar exploration base and the planetary exploration base are also both viable program possibilities. Were Apollo to discover resources which would minimize the logistics problem, the lunar base could move timewise into contention with the orbital exploration base. As far as the more distant future is concerned, we believe that ultimately the manned space flight program will encompass the exploration of some of the planets in our solar system. The principal characteristic that these missions will have, aside from the rather sizeable departure mass in earth orbit, is a very long duration and some rather formidable abort limitations once earth escape speed has been achieved. In line with our evolutionary concept of guidance and control developments, we believe that the capabilities and confidence needed for such missions must be developed and demonstrated in the earth orbital and lunar exploration programs.

NAVIGATION GUIDANCE AND CONTROL REQUIREMENTS

Considering these NASA missions in general and in the light of the obvious navigation, guidance, and control functions to be performed, we can define two general types of requirements. These are the mission flight-path control requirements and the mission-objective requirements. The mission flight-path control requirements are those requirements associated with transportation systems, that is, systems which are designed to deliver men and material to particular locations in support of specific objectives. It is obvious that the most demanding missions from a flight-path control point of view are the high-energy lunar and planetary missions. The lower energy earth-orbital missions, such as AAP, tend to have less critical flight-path control requirements. Apollo has demonstrated the navigation, guidance and control capability necessary to fly the high-energy flight paths. This performance capability, though not the system lifetime, has also been shown adequate for a manned planetary mission to Mars.[3]

The mission-objective requirements specify those capabilities needed to accomplish the objectives of the exploration bases. They can be demanding, or not, depending on the base's objectives. Apollo, for example, has few such requirements, for the Program's goal is to accomplish a manned lunar landing and return. This is in essence a transportation system flight-path control requirement. Some minor mission-objective requirements, such as inflight landing site photography, are included in the program but are structured such as to augment rather than interfere with the primary goal. The AAP and the earth orbital base, on the other hand, are heavily mission-objective oriented, and thus some of the most demanding navigation and control requirements resulted from this factor. The scope of our future navigation, guidance and control requirements, then, is encompassed by the types of transportation systems to be used and the objectives of the exploration bases to be developed.

Transportation Systems

The types of manned and unmanned primary and logistic/support transportation systems needed for various types of bases are shown in Table I. The principal elements of the AAP, which is in reality a small exploration base, are delivered to orbit

TABLE I
BASES FOR MANNED SPACE EXPLORATION

TRANSPORTATION SYSTEMS		EARTH ORBITAL		LUNAR		PLANETARY	
		AAP	EXPL BASE	LEP I & II	EXPL BASE	EARTH ORBIT ASSY	EXPL BASE
PRIMARY	Manned			SV/CSM-LM			Long transit times require all-up delivery
	Unmanned	SIB/OWS SIB/LM	SIC/SII / Base Elements	TIIIM / Lander	Base Elements	Base Elements	
LOGISTICS & SUPPORT	Manned	SIB/CSM	SIC/SIVB TIIIM / Shuttle	Lunar Flyer Lunar Rover	Base Personnel	Personnel	Transit to & from surface
	Unmanned		TIIIM / Exp Modules	TIIM / Lander	Base Equip & Expendables	Propulsive fuel	Transit to & from surface

by unmanned vehicles. The orbital workshop is delivered by a Saturn IB, and the Apollo Telescope Mount (ATM) is delivered by a combination of the Saturn IB and the lunar module (LM) ascent stage. The logistics and support function is provided by a manned command and service module (CSM) on a Saturn IB. The large earth orbital exploration base will make use of a similar transportation scheme with the base elements being delivered by unmanned Saturn V launches, but the logistics and support function could be accomplished by both manned and unmanned vehicles.

Conceptually, it is suggested that a permanent lunar exploration base will utilize the same pattern of unmanned primary element delivery with logistics and support functions being provided by both manned and unmanned systems. The early LEP does not follow this pattern, however. In this program we are attempting to deliver both the primary exploration elements and the personnel with single manned launches. As a result, we have a limited lunar exploration potential, of the order of several days with payloads of the order of 1,000 pounds. A limited increase in this exploration potential could be achieved by use of dual manned launches to a single site or with a Titan III launched unmanned lander. Both approaches have received some consideration. As pointed out earlier, the Lunar Flyer and Lunar Rover have been under study as manned support vehicles for the surface exploration.

We now come to the somewhat more nebulous planetary exploration base consideration. Studies to date have shown that we must first deliver multiple Saturn V payloads (3 to 12) to earth orbit and assemble them to get the required payload for any type of manned planetary exploration. Again, the same pattern of unmanned launches for the principal elements into earth orbit would appear a logical choice. However, we really have two transportation requirements in this case. The second one is the delivery of the exploration base from earth orbit to the planet. At this point, it would appear that due to the large transit times required, we should deviate from the previously established pattern and send our personnel along to husband and maintain the base enroute. This is a point that undoubtably will be considered carefully, though, before the actual rational to be used is eventually evolved.

It is possible to consider the earth orbital exploration base's transportation vehicle requirements a bit further. Table II presents the principal mission requirements for these vehicles.

TABLE II
LOGISTIC AND SUPPORT VEHICLE REQUIREMENTS
FOR EARTH ORBITAL EXPLORATION BASE

Resupply - 90 to 180 day launch centers (initial capability)
As required (ultimate capability)

Rendezvous, Reentry, & Landing - Manned and unmanned

Land Landing - Primary, with emergency water landing capability

Note that these requirements are principally the flight-path control type. The land landing requirement for manned vehicles will present a demanding navigation, guidance, and control consistency, for once the retrograde impulse is fired, the vehicle will generally be committed to some type of land landing. Current concepts for accomplishing these landings involve the use of unpowered, low subsonic L/D vehicles with a possibility of a limited powered go-around capability for more advanced versions. In either case, the vehicle must reach a specific site. The accuracy required at the end of reentry is not too demanding, however, being of the order 1.5 nautical miles one sigma to allow a successful terminal glide phase to the landing site with glide $L/D \approx 2.3$.[4]

The unmanned cargo delivery, as pointed out earlier, is an interesting requirement. Studies of an unmanned launch, rendezvous, and docking of the LM/ATM to the AAP workshop, as well as the Russian space program experience, have shown that this is a feasible technique. The LM primary guidance, navigation and control system with the rendezvous radar input has the requisite performance to deliver the LM/ATM to a station-keeping position approximately 1,000 feet from the orbital assembly. The LM Inertial Measurement Unit (IMU) is alined prior to launch and no further alinement is necessary throughout the three- to four-revolution rendezvous profile. Simulations of a manually controlled visual docking using a remote command link to the LM/ATM from the orbital assembly to bring it in from its station-keeping position have shown this to be a feasible technique using no instrumentation other than the out-the-window view. This technique, of course, is in contrast to the completely automatic docking method used in the Russian program.[5]

Exploration Bases

For the purposes of this paper, only the mission-objective requirements of the earth exploration base will be discussed. Table III presents the general mission profile requirements for the earth orbital base.

TABLE III
EARTH ORBITAL EXPLORATION BASE MISSION PROFILE

Altitude - 200 n. mi. to 300 n. mi. circular

Inclination - 50° to 90°

Duration - Two years minimum

The high inclination orbits will limit the amount of ground tracking available, assuming the present Manned Space Flight Network (MSFN) complex. The extended duration lifetime, even at the orbital altitudes contemplated, will undoubtably require a periodic orbit adjustment to counteract the orbit decay due to atmospheric effects. It will obviously also result in some rather demanding reliability requirements on the space station equipment. Notice in figure 2 that the average manned mission flight time

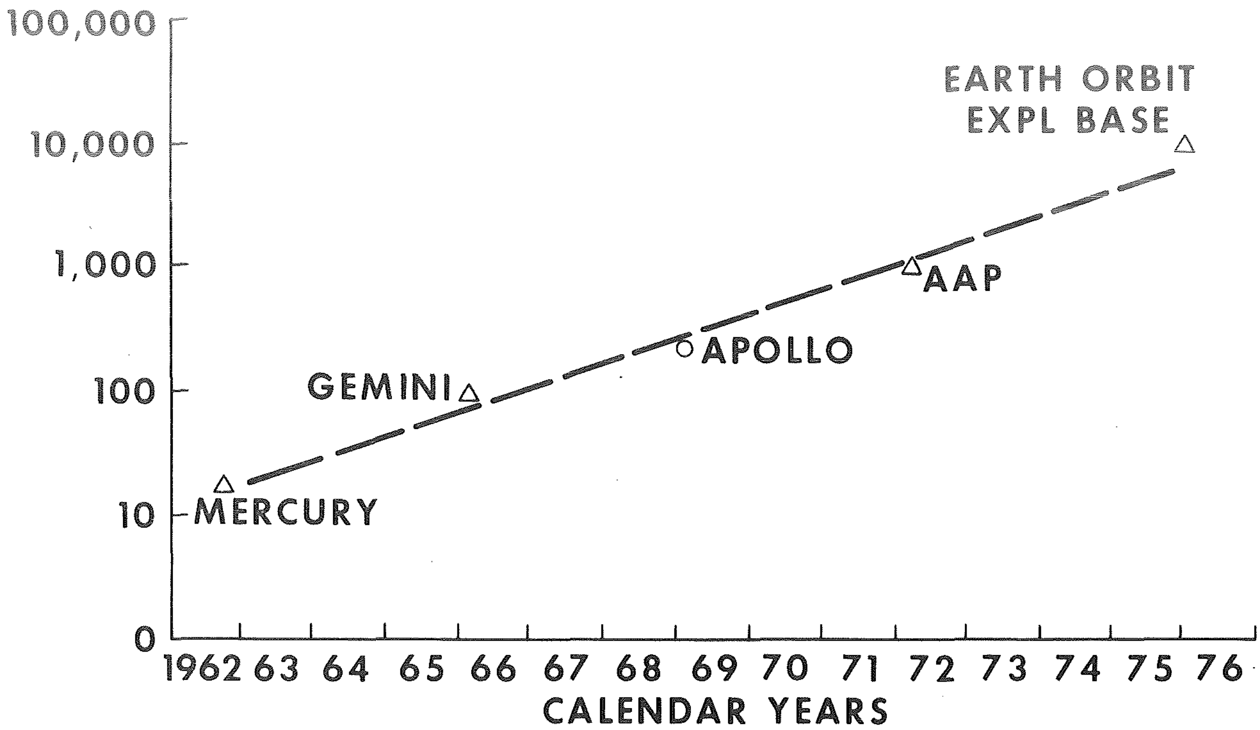

Figure 2. Average Earth-Orbital Program Flight Hours Per Manned Flight

increases approximately an order of magnitude between each of these earth orbital programs. Apollo's average manned mission time, as shown, is of the order of Gemini's. The impact from these increasing mission times on the system mechanization is an important factor and will be discussed later.

Mission Objective Requirements

The earth orbital exploration base mission-objective requirements are encompassed by the nine experimental program areas, Table IV, identified and documented by the NASA Space Station Requirements Steering Committee,[6] and developed and documented further in the Experiment Program for Manned Orbital Workshops prepared by the NASA Manned Space Flight Extension Working Group.[7]

The particular experiments, some of the experimental techniques, the instrumentation to be used in accomplishing them, and the resulting orbital base requirements have been studied and documented in several in-house and contracted studies. It is not within the scope of this paper to present a consolidated and detailed listing of these requirements nor to discuss the question of whether all of these requirements

TABLE IV
EXPERIMENTAL PROGRAM AREAS

Astronomy/Astrophysics
Earth Resources
Atmospheric Sciences
Physical Science
Advanced Technology and Subsystems
Manned Space Operations and Logistics
Communication/Navigation/Traffic Control
Biomedical/Behavioral
Bioscience

should be met on a manned space base. They have been reviewed, however, in an attempt to establish bounds. The orbital base mission-objective requirements are most closely related to the navigation and the control functions, with the guidance function being of secondary importance.

Pointing Control Requirements: Considerable attention has been directed at the pointing control requirements, and figure 3, prepared from data in contractor report NASA-CR-92299 entitled "Combined Mission Requirements. Saturn V Single Launch

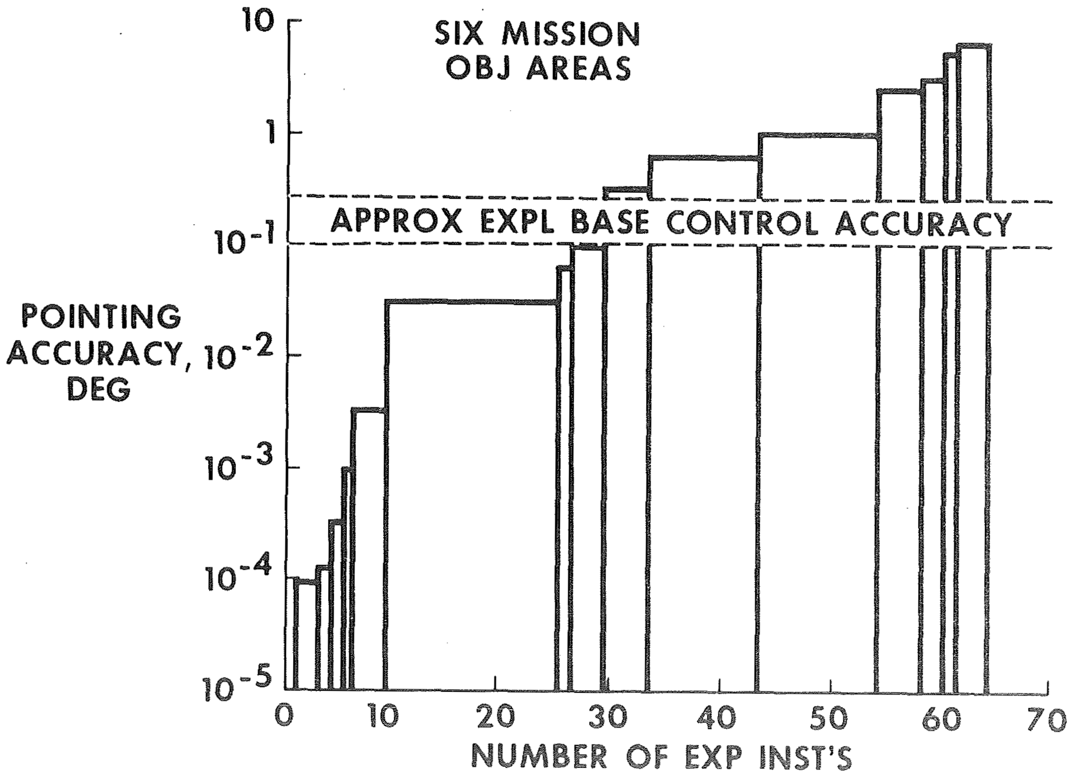

Figure 3. Earth-Orbit Exploration Base Cumulative Pointing Accuracy Distribution, Six Mission-Objective Areas

Space Station and Observation Facility," shows the cumulative distribution of pointing accuracy requirements for six experimental areas. Since we do not expect to be able to control the space station itself to an accuracy of less than one-tenth to one-half of a degree, about half of the experimental instruments will have to independently provide the pointing accuracy they require. Also, this value of space station accuracy is with respect to the attitude sensor mounting pads. Because of thermal distortions and other effects, it is not likely that this accuracy will be available at any given space station position. For example, studies[8] of a horizon scanner installation at the base of the CSM showed that the vehicle had a distortion of about 0.35 degree from one end to the other when the cylindrical axis of the spacecraft was normal to the sunline with no roll rate. This vehicle distortion resulted in a sensor misalignment with respect to the navigation base of twice this angle. These requirements represent different reference frames (e.g., local vertical stellar-inertial). Because of the different reference frames, a zero-g orbital base will have segments which must be attitude controlled in the presence of three different rates, and an artificial g orbital base will have an additional one. These rates are as follows: (a) inertial, (b) orbital rate, (c) orbital regression rate, (d) spin rate. The requirement to simultaneously satisfy many different pointing requirements has been a challenge in the past and shows promise of being a sizeable task for the space base in the future.

Navigation Requirements: In all considerations of experiments, there has been little attention directed at the question of what the required navigational accuracy was, or if, in fact, any navigation requirements existed at all. Apparently, it is assumed that since the space station is in a relatively fixed orbit, we will always know where it is. This is essentially true. However, the primary questions to be asked are how well do we have to know where it is, who has to know, and when do they have to know? Only by answering these questions will we be able to determine how we shall provide this knowledge. Thus, the available information on the contemplated experiments has been reviewed in an attempt to determine the explicit and implied navigation requirements. Table V shows some of these results.

Although much of this information is descriptive rather than quantitative, it nevertheless indicates a need for navigation information in real time, on board the orbital base for experiment support. The positions of the various celestial bodies of concern (e.g., earth, sun, moon), and the time that particular earth sun lighting conditions occur cannot be determined without knowing what the orbital base's position is with respect to the chosen reference frame. The appearance of unwanted celestial bodies in the field of view of an instrument during the exposure of a film plate must be avoided by maintaining a reasonable amount of ephemeridics information on board. Tracking ground targets automatically from the space station also requires an accurate knowledge of the spacecraft's position. There are two quantitative requirements which will be very difficult to achieve. The first is the requirement to know relative position to 5 to 10 meters over ranges of 1000 to 2000 nautical miles. It results from the need to limit cartographic error propagation when tieing large numbers of sequential photographic frames together. The other requirement, position knowledge to 100 meters, results from a stellar refraction experiment used to obtain atmospheric density data. In view of the fact that the position of the MSFN stations themselves is generally not known to better than 75 to 150 meters in longitude, meeting these requirements will be a challenge.

TABLE V
EARTH ORBITAL BASE
MISSION-OBJECTIVE NAVIGATION REQUIREMENTS

Mission Objective	Navigation Requirements
Astronomy/Astrophysics	Dark side of orbit $>90^\circ$ from sun Sun side of orbit Avoid earth occultation
Earth Resources	Near local noon Daytime Sun angle 30° above horizon Track 2 to 10 targets per orbit Know relative position to 5 to 10 meters over ranges of 1000 to 2000 nautical miles
Physical Sciences	Deploy and retrieve subsatellites Sun orientation
Atmospheric Sciences	Avoid sightings just prior to dawn Sun angle $>10^\circ$ Know position to 100 meters Navigate to <2.0 n. mi.
Comm/Nav/Traffic Control	Track synchronous altitude satellite Point narrow beam antennas Point lasers
Manned Space Operations & Logistics	Data capsule returned to selected site

GUIDANCE, NAVIGATION AND CONTROL MECHANIZATION CONSIDERATIONS FOR EARTH ORBITAL SYSTEMS

In the foregoing limited discussion of requirements for the advanced programs under consideration, there are several quantitative guidance, navigation and control requirements that may be difficult to meet. To a large extent, however, we have demonstrated much of the GN&C performance these programs require so the principal mechanization challenge for the future will not be in meeting discrete performance requirements. It is going to result from the need to achieve extremely difficult reliability goals. The interesting thing about these reliability goals for the future is that they will, more than ever before, be intimately associated with program costs. This is a result of the extended duration operational characteristic of the exploration bases. As the number of transportation flights becomes large, the possibility of incurring a failure in the guidance, navigation and control system increases. If the mission must be aborted due to such a failure, the cost of that failure can be quite substantial. Thus, it is necessary to make the transportation system guidance and control system reliable enough to keep the frequency of such failures very low. In addition, for very long space base operational times, the replacement rate for the on-board guidance, navigation and control equipment is defined by the equipment failure rate. Thus, to minimize the cost of keeping the system operational, it must be kept as simple and as reliable as possible. Coupling these factors with the need to minimize the guidance, navigation and control overall recurring costs by not over specifying requirements and by reusing equipment that has flown, then gives us an indication of the nature of our future mechanization challenge.

Transportation Systems

In discussing the GN&C mechanization considerations for transportation systems, it is informative to first consider the approach used and the experience gained in our first three manned space transportation systems — Mercury, Gemini, and Apollo. Efforts were made in the guidance and control developments for each of these programs to avoid single point failures which could have catastrophic consequences. Due to limitations in the available state of the art, however, coupled with severe payload restrictions, it was not possible to place equal emphasis on minimizing the probability of crew loss and on maximizing mission success. Thus, for all three programs the requirements for crew safety were higher than the requirements placed on mission success. Because of the environmental unknowns inherent in each program and the fact that each one was largely developmental in nature, this ordering of reliability requirements was both desirable and necessary. In fact, since the principal purpose of these transportation systems was crew delivery to station and return, it could even be argued that the mission success was not severely compromised. The general approach used was to have a high-performance simplex primary system backed up by several degraded performance backup or abort modes. The mission guidance and control reliability was largely defined by the primary system and the crew safety by the reliability of the parallel backup modes. Conceptually, the rational for this type of mechanization was that the degraded performance backup systems, being simpler, would have a higher reliability and thus be less likely to fail than would the primary system. In addition, the possibility of a catastrophic failure of the total guidance and control system would be minimized because of the use of generically different hardware in the mechanizations. In practice, this mechanizational approach, coupled with a careful and meticulous flight hardware qualification and verification prior to flight, has worked extremely well as attested by the remarkable string of successes achieved in these programs to date.

As the missions became more complex, however, some undesirable constraints associated with this approach began to evidence themselves, particularly on Apollo. One result of this type of mechanization was that the lower performance systems tended to require more fuel to accomplish given functions than did the higher performance guidance and control systems. The command module's computer-mechanized digital autopilot, for example, which can refrain from firing reaction control system jets in opposition, requires approximately 20 percent less fuel, at a typical command and service module center of gravity offset, than does its analogue control system which does not have this logical capability. Another problem results in trying to use a less accurate backup system to monitor a primary system. It is sometimes necessary to limit the capability of the primary system so that the lower performance backup system can be used to monitor it. For example, it is necessary to prohibit the primary guidance and navigation system from flying some satisfactory reentry trajectories because the Entry Monitor System (EMS) cannot discriminate between these satisfactory trajectories and those that result with a particular type of guidance and navigation system failure. An additional problem associated with the EMS when it is used to guide the reentry is that the touchdown range dispersion is greatly increased over that achievable with the primary system, although crew safety is not compromised. A final problem associated with this type of mechanization philosophy also involves the crew interface with the GN&C systems. On both Gemini and Apollo, much time, effort, and training has gone into developing techniques, procedures, rational and logic for monitoring, failure detecting, and switching from the simplex primary G&N system to the various abort or backup options. In each time-critical G&C operation such as rendezvous, LM descent, and entry, the procedure development and training problem has been compounded by the multiple backup modes and the need to integrate the ground tracking and command capability with the various degraded onboard options. At time-critical points in the mission profiles, time-lines have been stretched out and functions to be accomplished have been compartmentalized to allow the monitoring function to be accomplished. This compounded crew interface problem has largely, although admittedly not entirely, been decreed by this type of system mechanization. Even after carefully and systematically developing these procedures and interfaces, we are still continually faced with a remote possibility of failure of the simplex primary system in the middle of a time-critical operation and are strongly dependent on the crew's ability to respond properly under stressful conditions for crew safety and success of the mission.

In view of the foregoing constraints and limitations, a great deal of study should be directed towards the design of guidance, navigation and control systems utilizing true redundancy techniques for future transportation systems. These studies should have as a goal the achievement of mission success and crew safety reliability requirements which are equivalent. The Apollo Saturn V launch vehicle already uses some redundancy techniques in both its guidance and control systems.[9] The launch vehicle computer, for example, has triple modular redundancy (TMR) which allows it to continue functioning despite failures in discrete modules.

To supplement the Saturn launch vehicle redundant control system experience, we will be looking to the aircraft industry in general and the supersonic transport developments in particular, since our advanced transportation system reliability objectives will parallel those that they have been concerned with for a number of years.[10 11 12 13] The possible use of redundant inertial navigation systems in the air transport industry is only now beginning to evolve. Current considerations for the supersonic transport include both multiple gimballed inertial navigation systems and redundant strapdown systems.[14 15] In fact, the economic requirements of the supersonic transport that dictate the need to complete its mission profile despite discrete navigation failures parallels in kind, though not necessarily in magnitude, our economic need to complete transportation missions. The redundant strapdown system, either in the form of two or more triads, or as a single system using six gyros and six accelerometers arranged nonorthogonally,[16] which can sustain multiple failures of gyros and accelerometers and still keep functioning, shows promise of very nicely solving the redundant inertial sensing problem for the earth orbital logistics shuttle. In fact, it could probably be shown that one such redundant inertial measurement unit, mounted in the Apollo command module and properly integrated, could provide the functions of the G&N inertial measurement unit, the six-body mounted gyros in the SCS, and the ST124 inertial measurement unit platform in the Saturn launch vehicle with an improvement in system reliability. Since the redundant strapdown unit would replace 12 gyros, 7 accelerometers, and 6 gimbals, there is little doubt that the weight and power trade-off would be in its favor, even accounting for the additional computational complexity incurred. Of course, the cost of implementing this change at this point in the Apollo Program's development could never be amortized over the remaining Program lifetime and so it would not be done. The potential of this integrated approach for the future, however, can hardly be ignored. The additional cost, both nonrecurring and recurring, to achieve the redundancy can be traded off against the cost of G&C failure over the transportation system's lifetime.

As a last point concerning the mechanization aspects of transportation systems, the control equipment that is jettisoned with expendable launch vehicle stages must be minimized to reduce recurring costs.

Orbital Base

We have as yet had no experience in operating space exploration bases. The AAP will be the first of these, though it will be relatively small and have a somewhat limited lifetime. It has some interesting control system pointing requirements which require the principal experimental apparatus to be gimballed with respect to the spacecraft and controlled to the instrument sight line while the spacecraft itself is controlled with respect to inertial space by relatively large two-degree-of-freedom control moment gyros. The required accuracy of control on the instrument sight line is ± 2.5 arc seconds in pitch and yaw while the spacecraft is controlled to ± 4 arc minutes about the same axes against crew disturbances and other spacecraft disturbances. This method of using tiers of control systems ranging from a coarse to a fine control accuracy is expected to be characteristic of the control system distribution to be used in the orbital base. Thus, the results to be gained from the actual flight experience of the AAP will be of considerable interest. The program has few mission-objective navigation requirements, however.

The earth orbital exploration base will in essence be an orbiting facility itself, and thus can be expected to have a rather sizeable computation facility on board. In fact, it is conceivable that, in the time period under consideration, the orbiting base computational capability could approach the capacity and computational flexibility of some of our present ground computer installations. In view of the expected time-varying nature of many of the activities on board the space base (experiments will come and go), it is expected that the computational facility will have to expand and contract as necessary to provide the needed computational support efficiently. The multiprocessor[16] shows promise of providing this needed flexibility as well as on-line redundancy when required. The variation in capacity can be accomplished on a short-term basis by putting modules on-line or off-line as the computational demand varies. This would conserve power and minimize equipment operating time. Additionally, in the longer term, the capacity could be expanded or contracted by physically adding or removing computational modules, provided the interfaces were appropriately arranged. It will undoubtably be highly desirable also to standardize the types of computational modules and use them in both the space base and the transportation shuttles. This approach would provide the advantage of interchangeability for maintenance purposes and would have some economic and reliability benefits which would accrue from the larger production volume.

There are some unique computational requirements, however, having characteristics that a centrallized general purpose computational facility cannot gracefully handle. These are generally associated with subsystems having large bandwidth and relatively fixed format computational needs and which in addition often require complex input-output interfaces. One example is the computational requirements of a complex general-purpose display system, which must have a variety of format generators and a large repetition rate associated with its information input. The multipurpose display, incidently, is an extremely important requirement for the space base. In the past an inordinately large penalty in weight, volume, and power was paid for multitudes of single purpose displays that were used at only singular points in the mission profiles. The total weight of all panels, instruments, and switches on the CSM, for example, approached the total weight of the G&N system. The multipurpose display is also applicable to the transportation shuttle to some degree. Because the shuttle's display requirements and the shuttle operator's experience will be very similar to those of aircraft, however, the degree of applicability requires a careful assessment. Other examples are associated with sensors having unique processing requirements, and control computers having complex input-output requirements and transmission problems associated with sending a variety of signals to different types of torquers. For these special requirements, it may be advisable to use computational modules which are tailored to the need. Conceivably, they could be under the master control of the central processor but could also maintain a degree of autonomy which would allow them to continue functioning in the event of serious problems in the central processor.

With the availability of an onboard computational facility, it should be possible to use the best orbital navigation models available in the time period to propagate the base's state vector. In fact, the models could be changed at any time if better ones became available. Therefore, the decision of which navigational system mechanization to use should not be constrained by a need for onboard computational efficiency. The problem then reduces to the sensing question. How shall the initial conditions be established, and what shall be the means used to periodically update the propagated state vector to bound the navigational error? In attempting to answer this question, we are confronted with the dichotomy of the flight controller/ground tracking complex and the astronaut/onboard navigation system. Apollo's flight experience is in the process of providing additional knowledge for those who would care to pursue the question from either point of view. The question of which to use on the space base cannot be resolved in this paper, however, since the answer transcends the navigation question alone, and becomes involved in the overall data transfer question. It is known that MSFN, due to its predominately low latitude distribution, provides a spotty and low-percentage coverage for orbital inclinations in the 50° to 90° range. This fact will not only limit the amount of ground tracking available for updating the space base's state vector, but will severely constrain the information transfer capability. There are two possibilities for removing this information transfer constraint. One is the use of a synchronous orbit data relay satellite system,[17] which would allow continuous communication between the space base and a mission control ground station. The space base, with some additional pointing control complexity invested in tracking communications antennas to allow a high bandwidth information rate (e.g., 0.1 to 4 megabits per second), could also generate its needed navigational updates by tracking the synchronous satellites, although the accuracy achievable by this method has still to be defined. The other possibility is to remove the need for the high information rate transfer by doing most of the required data processing with the onboard computational facility. The required navigational updates would then be generated with a suitable combination of stellar and earth sensors.

Assuming the required navigation sensing method to be used is based on a combination of earth sensors making measurements in an inertial reference frame, some early results from our flight experience should be considered. Tracking landmarks manually is an undesirable chore. Once the astronaut has demonstrated that he can update his state vector as well or almost as well as MSFN can, he isn't interested in doing it repetitively except in cases where he is highly motivated — such as making sure personally that he is really going to hit the reentry corridor — or that his lunar orbit insertion point is a respectable altitude above the surface. Keeping track of where the space base is by tracking three or more landmarks per orbit, every orbit, will not generate a desire in many astronauts to earn space navigators wings. In addition, orbital manhours will be expensive in the orbital base and should be used in more beneficial tasks. Thus, though we can expect the crew to provide the acquisition function and to periodically monitor the navigation system, it should be basically automatic in its operation.

At this point it is necessary to touch on the need for simplicity. The cost of the navigation, guidance and control system maintenance activity, including the spare parts, will be defined by the equipment failure rate and the logistic system delivery costs. Even the ultimate figure of 5 dollars per pound into orbit, which is often stated as a goal, substantially exceeds the airfreight rate for shipments going 250 miles. It is imperative that the system mean-time-to-failure be extremely long. Furthermore, at any point in the lifetime of the space base, it should be possible to estimate whether the cost of installing a given new system with a lower failure rate can be amortized over a given number of years. If the savings to be expected are still substantial after accounting for the usual uncertainties in cost estimates, then it would be expected that the change would be made. For this approach to be feasible, however, it is evident that the space station interfaces such as power, cooling, etc., must be given more than the usual considerations.

CONCLUDING REMARKS

There is little doubt that the manned space flight program, after overcoming several developmental challenges, has reached, or is about to reach, a plateau of operational usefulness. The guidance and control systems developed for these previous programs have already demonstrated much of the performance that is going to be required on this operational plateau. In the far distance are some additional manned guidance and control challenges which show promise of being very interesting. However, before we can address ourselves to them, we must first develop the ability to provide the performance and capabilities required in the immediate future in an economically tenable manner. If we can achieve this near-term future goal, we will in effect have solved many of the problems facing us in the far future. The most difficult challenge of the far future is the manned planetary exploration base, for it combines the time-critical guidance and control reliability requirements of our earth-moon system transportation vehicles and the long-duration reliability requirements of the earth orbital exploration base in one self-contained package. By solving these problems in the earth orbital exploration base, we should be able to configure our planetary exploration base guidance and control systems in such a way that time-critical flight operations can be conducted with the necessary system redundancy and so that operational readiness can be assured with maintenance in non-time-critical flight phases. With enough operational experience in the earth orbital exploration base, we should be able to predict quite accurately the types and numbers of spares (either wired in or replaceable) required so that when our planetary exploration expedition returns and is faced with that last time-critical guidance and control phase, we will have sent along enough spares so that the reentry can be accomplished with all-components-up redundancy.

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